Heat Transport Through Superconducting Quantum Circuits:

Experiments and Local vs Global Picture of an Open Quantum System

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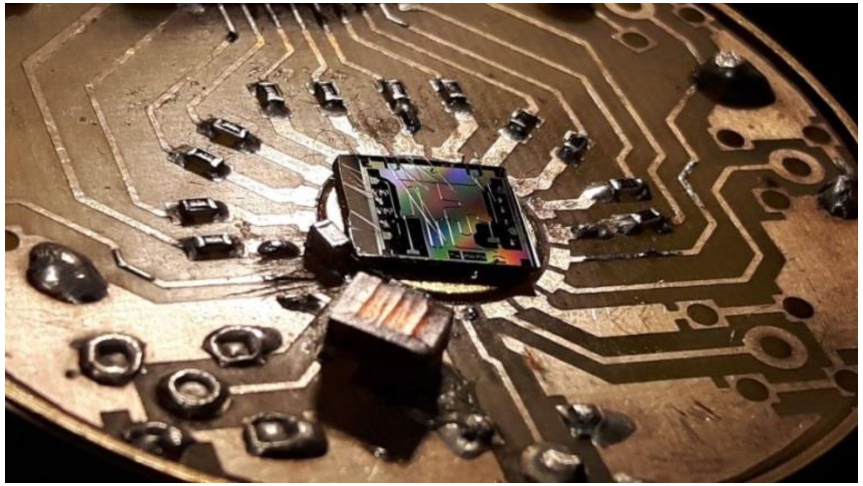
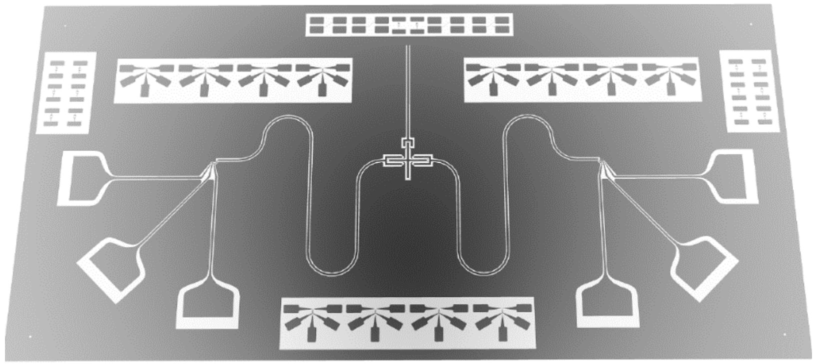
1. Heat in circuits: measurement and control
2. Thermometry
3. Quantum of heat conductance, quantum heat valve, local and global picture, rectification of heat current
4. Quantum Otto refrigerator

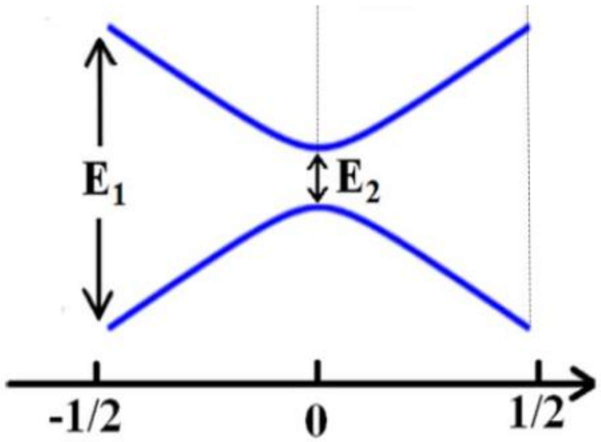


Qubit as an open quantum system

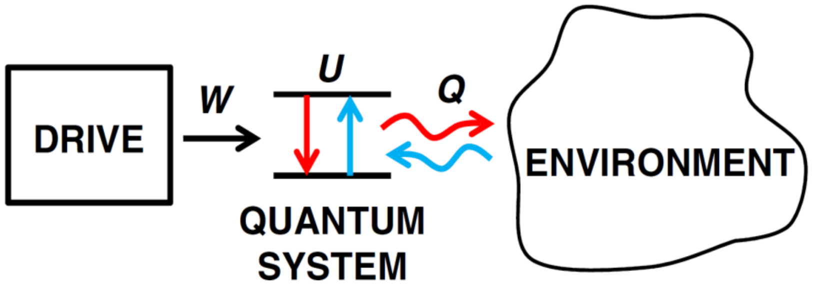
Superconducting qubits



$$H_{\mathrm{Q}} = -E_0(\Delta\sigma_x + q\sigma_z)$$

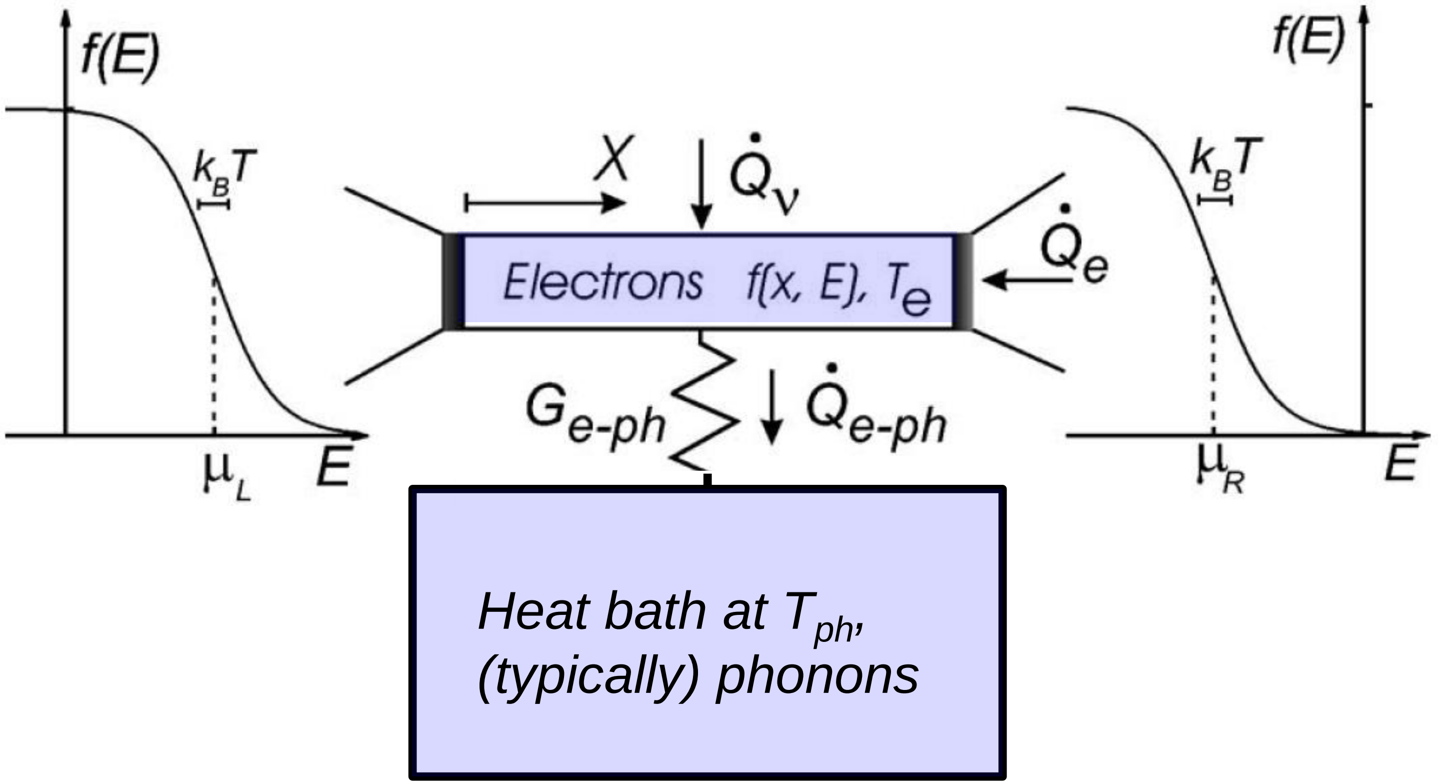


$$q \equiv \delta\Phi/\Phi_0$$



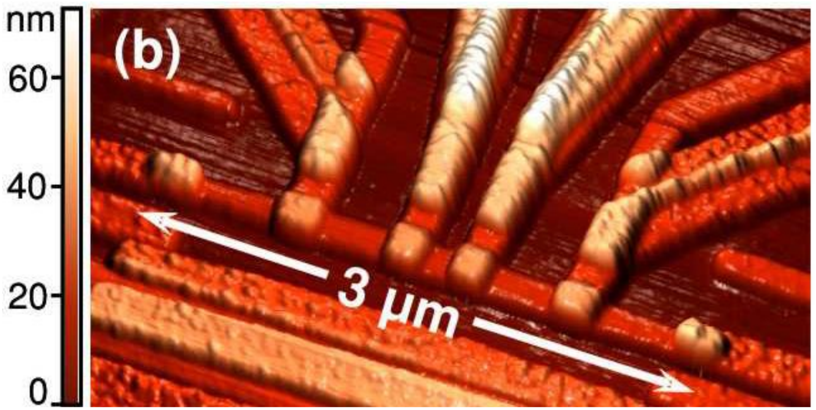
$$H = H_{\mathrm{Q}} + V + H_{\mathrm{E}}$$

Generic thermal model of an electronic reservoir



Temperature of the (electron) system given by the distribution:

$$f(E) = \frac{1}{1 + e^{(E-\mu)/k_BT}}$$

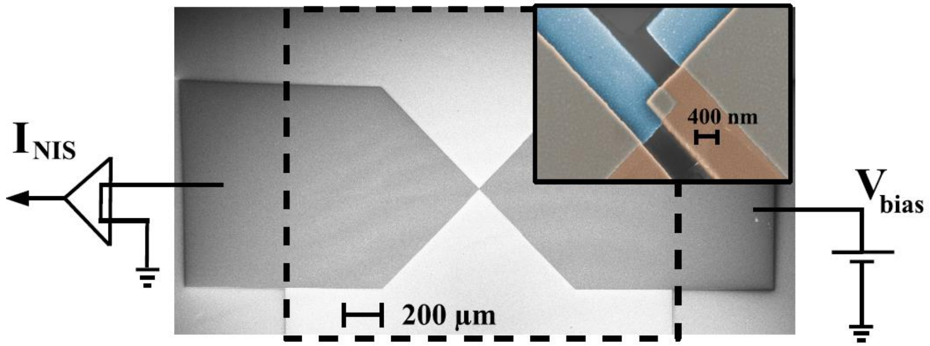


Separation of time scales: $\tau_{ee} < 10^{-9}$ s, $\tau_{ep} > 10^{-6}$ s

NIS-thermometry

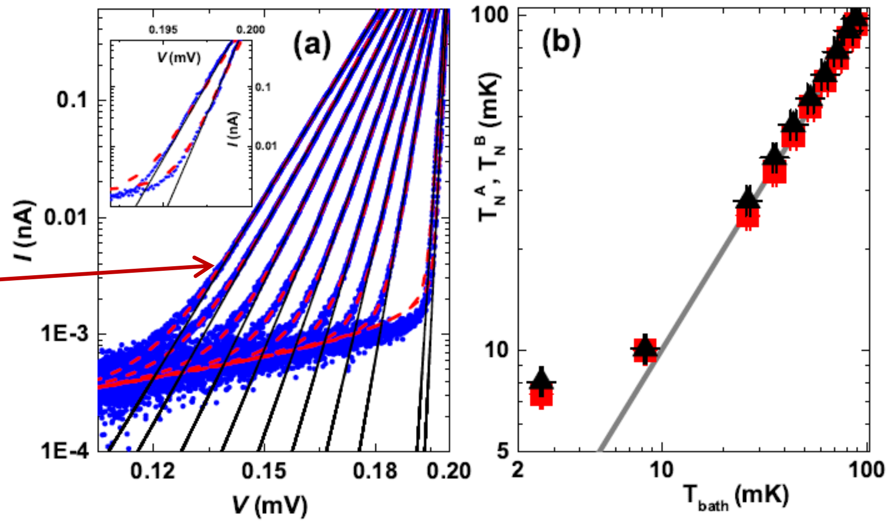
$$I = \frac{1}{2eR_T} \int n_S(E)[f_N(E-eV) - f_N(E+eV)]dE$$

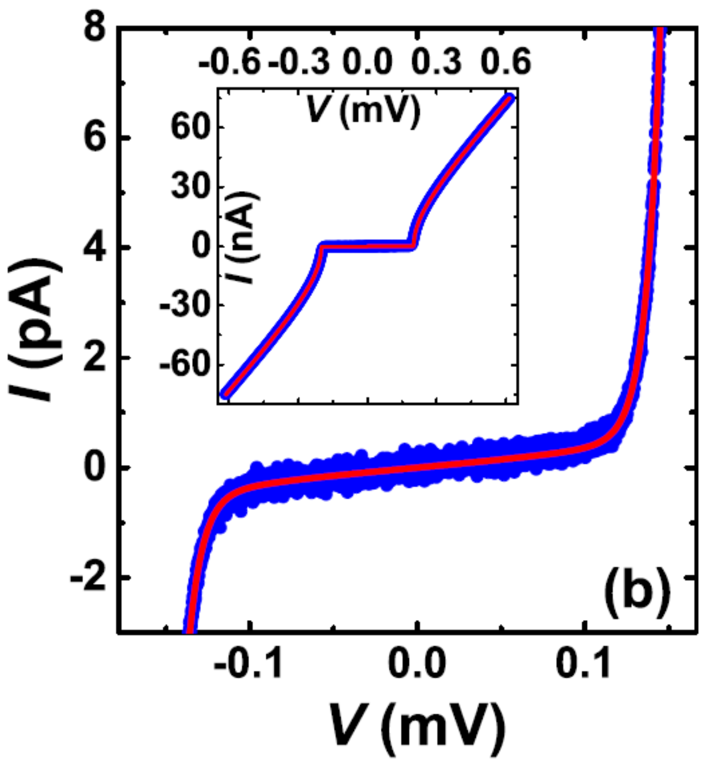
Probes electron temperature of N electrode (and not of S!)



$$I \approx I_0 e^{-(\Delta - eV)/k_B T}$$

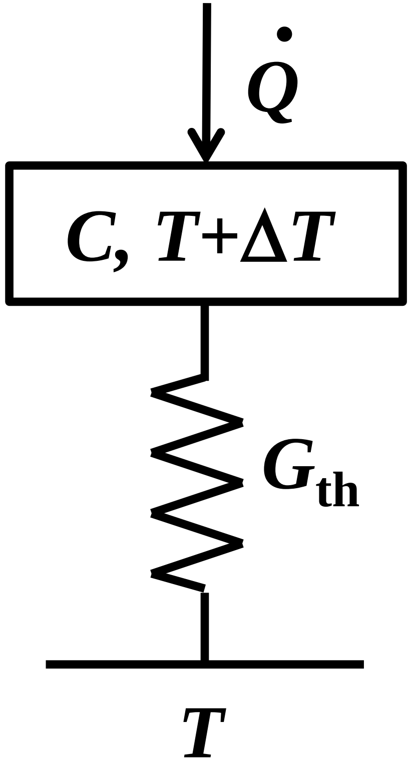
$$\frac{\mathrm{d}\ln(I/I_0)}{\mathrm{d}V} \approx \frac{e}{k_B T}$$



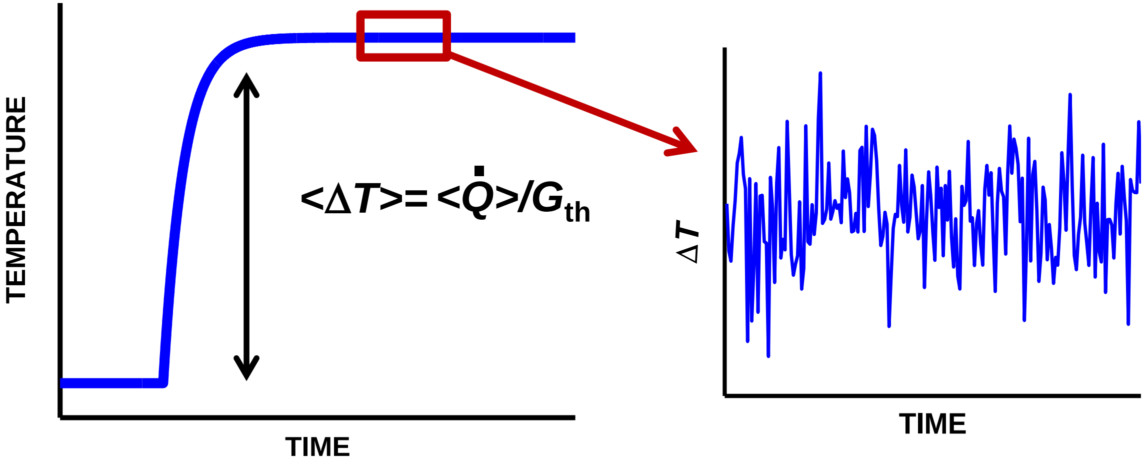


Phys. Rev. Appl. 4, 034001 (2015).

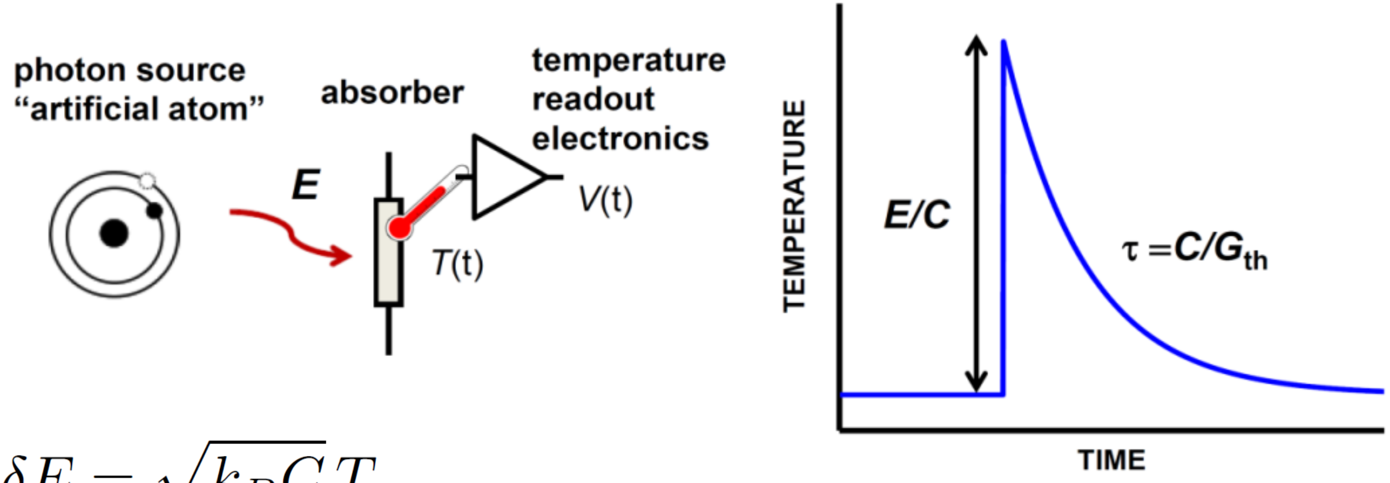
Measuring heat currents



Measurement of temperature by a (fast) thermometer



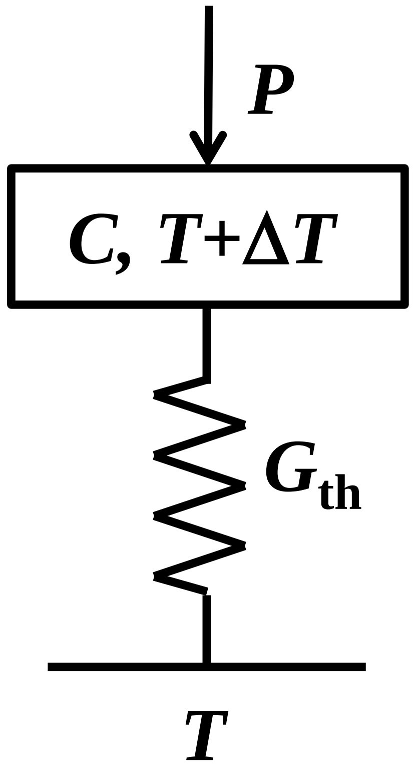
Single quantum detection (calorimetry)



Energy resolution:

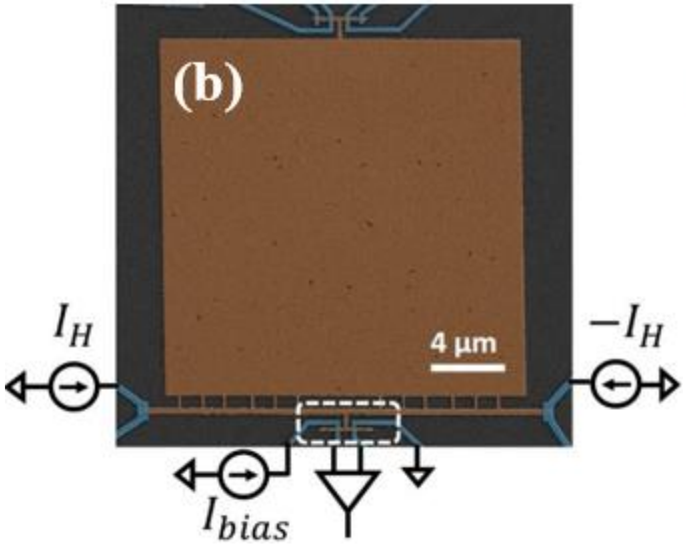
$$\delta E = \sqrt{C G_{\mathrm{th}} S_T} \quad \text{ideally} \quad \delta E = \sqrt{k_B C}\, T$$

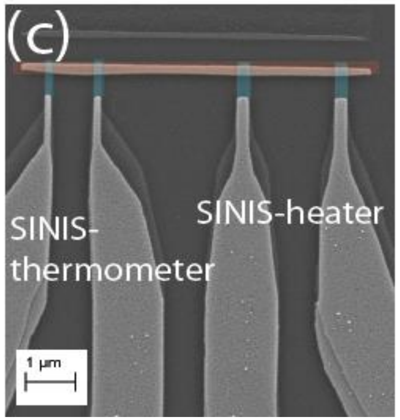
G_{th} - electron-phonon coupling

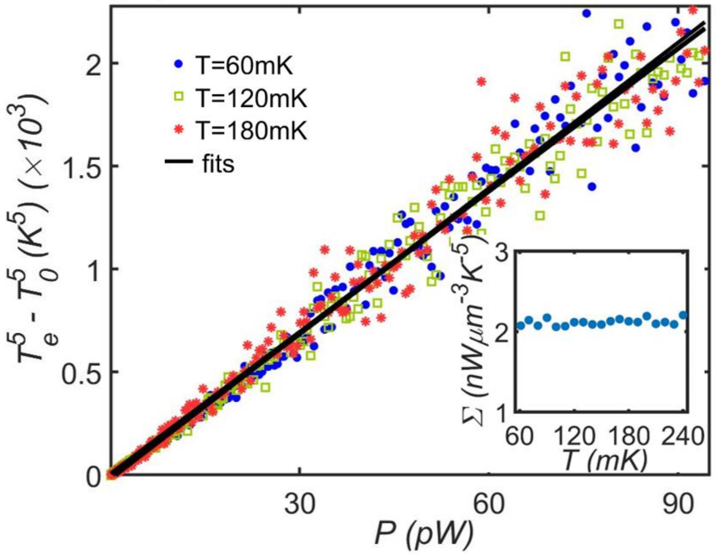


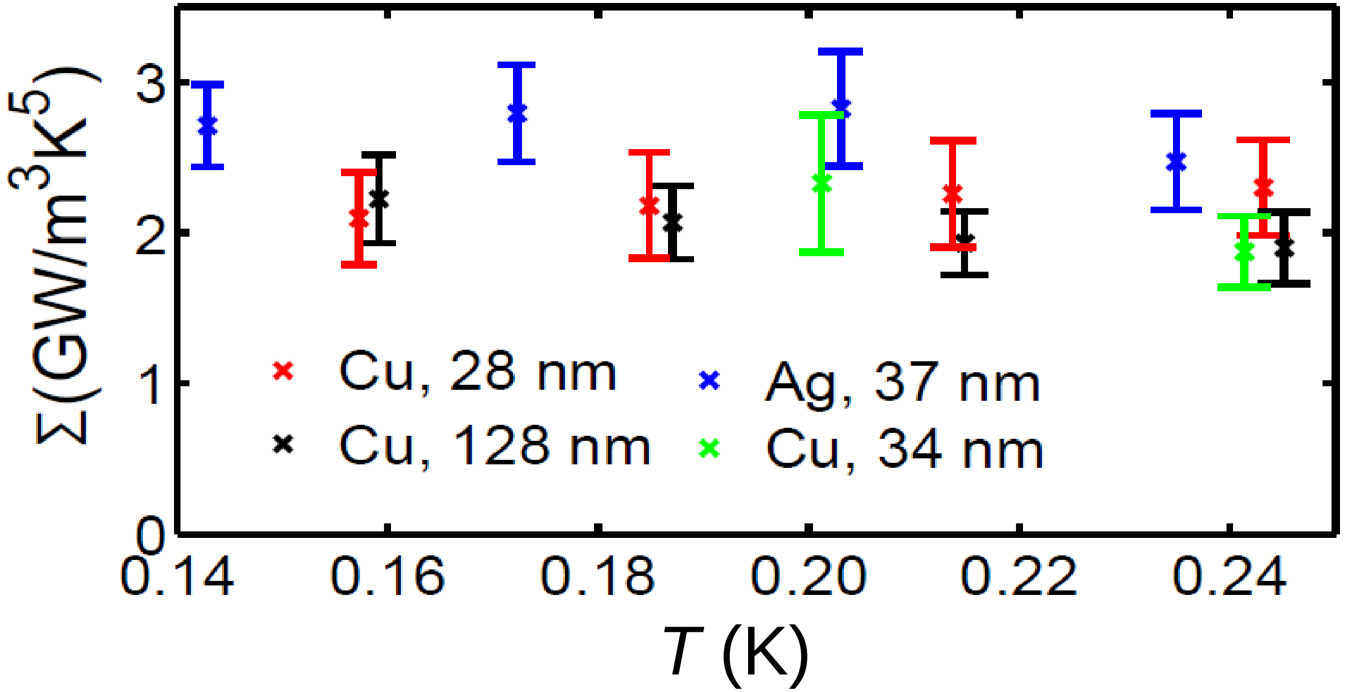
$$\dot{Q} = \Sigma \mathcal{V}(T_e^5 - T_p^5)$$

$$G_{\rm th} = 5\Sigma \mathcal{V} T^4$$







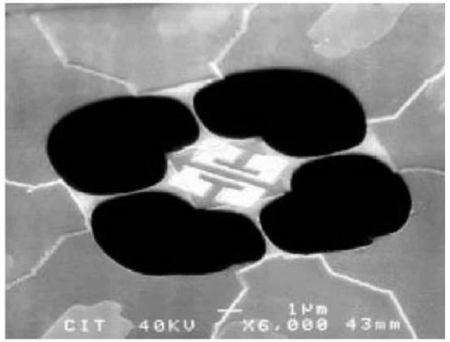


M. L. Roukes et al., PRL 55, 422 (1985)
K. Viisanen and JP, PRB 97, 115422 (2018)
L. B. Wang et al., arXiv:1903.10848

Quantum of heat conductance

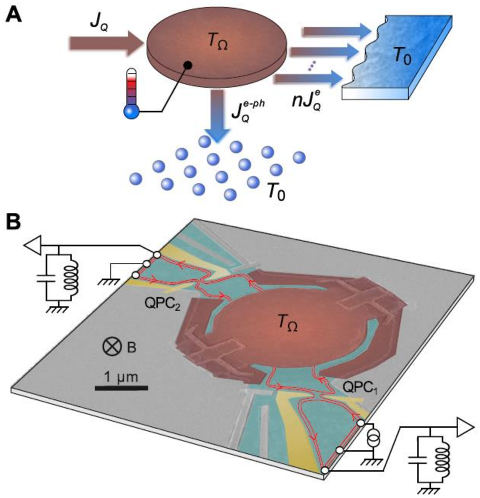
$$G_{\mathrm{Q}} = \frac{\pi k_{\mathrm{B}}^2}{6\hbar} T$$

J. Pendry 1983



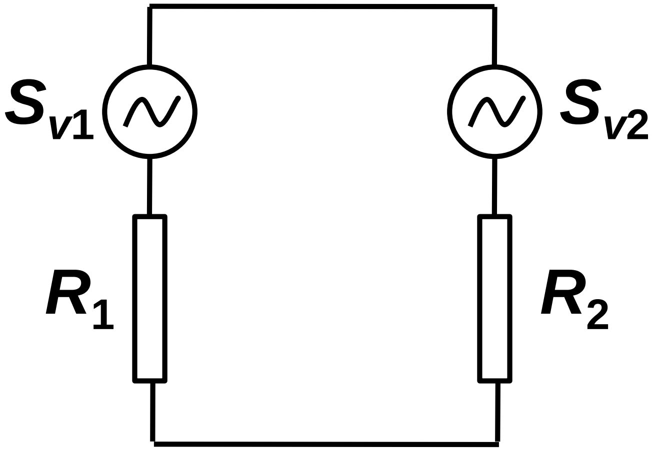
Phonons
K. Schwab et al., Nature 404, 974 (2000)

Photons
Schmidt et al., PRL 93, 045901 (2004)
Meschke et al., Nature 444, 187 (2006)
Timofeev et al., PRL 102, 200801 (2009)
Partanen et al., Nature Physics 12, 460 (2016)



Electrons
Jezouin et al., Science 342, 601 (2013)
Banerjee et al., Nature 545, 75 (2017)

Heat transported between two resistors (photons)

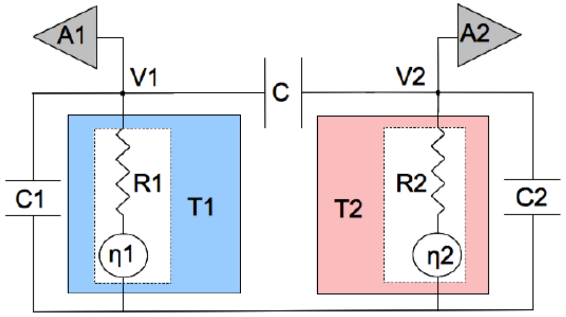


Johnson-Nyqvist problem – classical and quantum

Power transferred from 1 to 2

$$P_\nu = \int_0^\infty \frac{d\omega}{2\pi} \frac{4R_1 R_2 \hbar\omega}{|Z_t(\omega)|^2} \left(\frac{1}{e^{\hbar\omega/k_B T_1} - 1} - \frac{1}{e^{\hbar\omega/k_B T_2} - 1} \right)$$

Classical regime:



$P = K\,\Delta T$

S. Ciliberto et al., PRL 110, 180601 (2013)

Quantum regime:

$$P_\nu = r \frac{\pi k_B^2}{12\hbar} (T_1^2 - T_2^2)$$

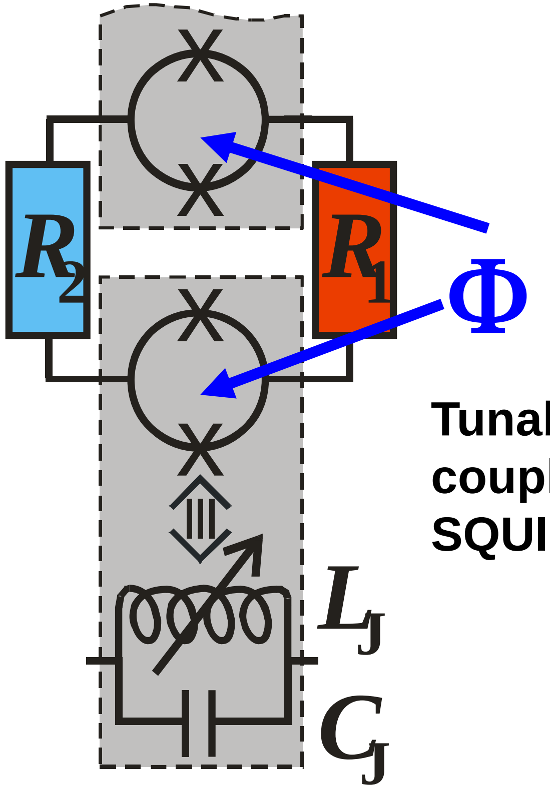
$$r \equiv \frac{4R_1 R_2}{(R_1 + R_2)^2}$$

Linearized for small *T*-difference:

$$P_\nu = r G_Q \Delta T$$

$$G_Q = \frac{\pi k_B^2}{6\hbar} T$$

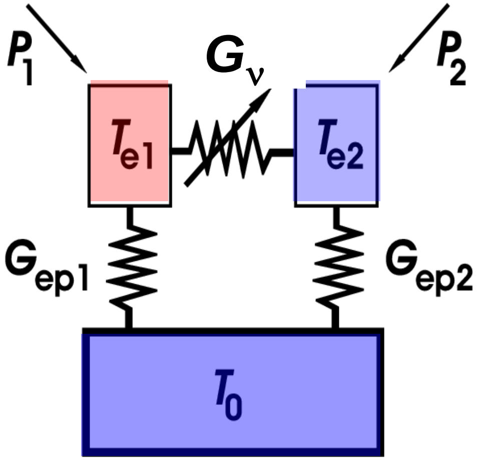
Experimental realization of photonic heat transport

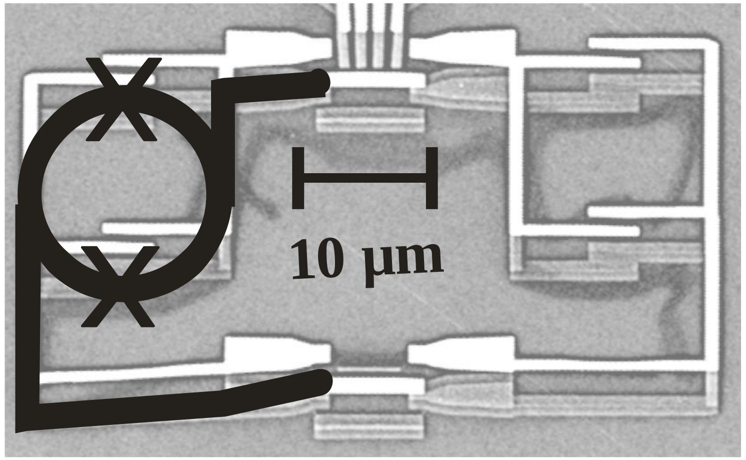


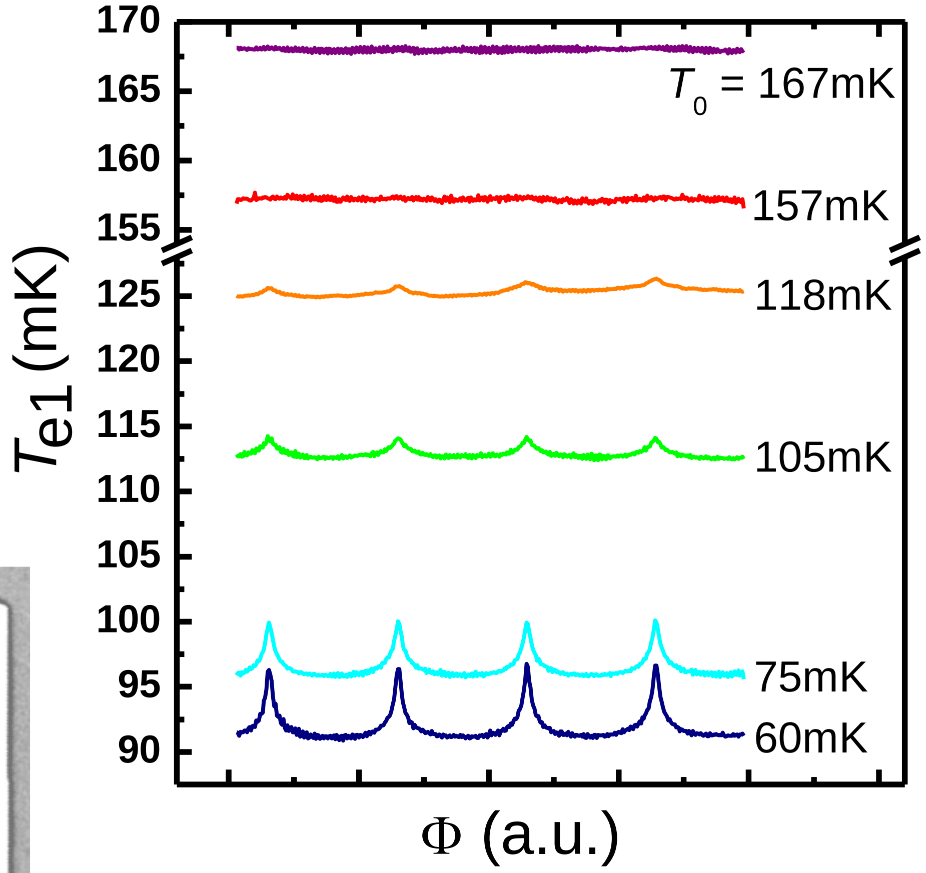
Tunable coupling using SQUIDs

$$L_J = \frac{\hbar}{2eI_{C,0}|\cos(\pi\Phi/\Phi_0)|}$$

Thermal model

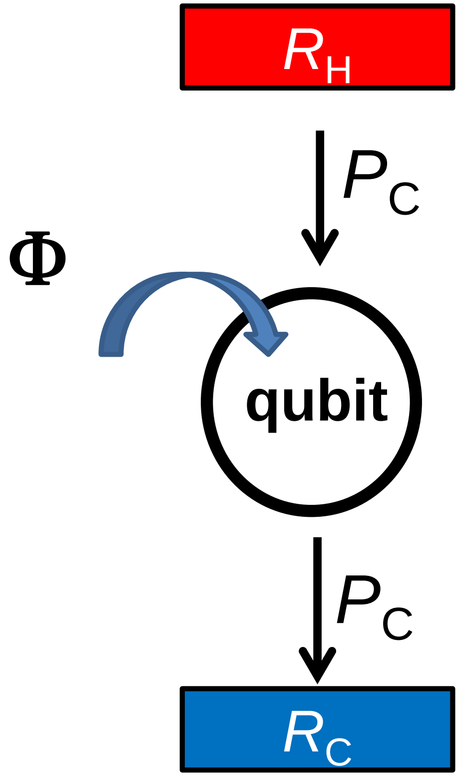




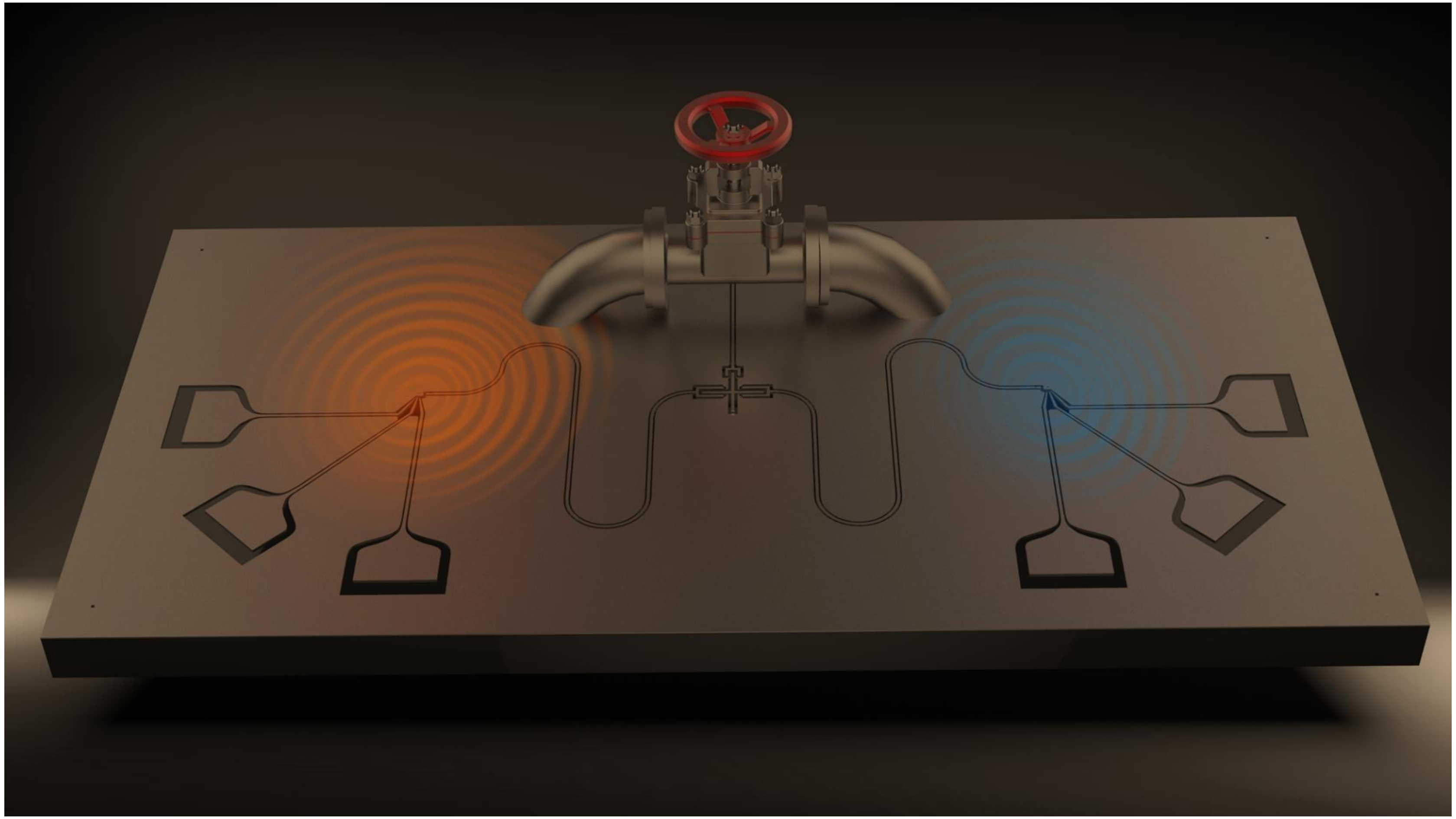


Meschke, Guichard and JP (2006)

Quantum heat valve by a superconducting qubit



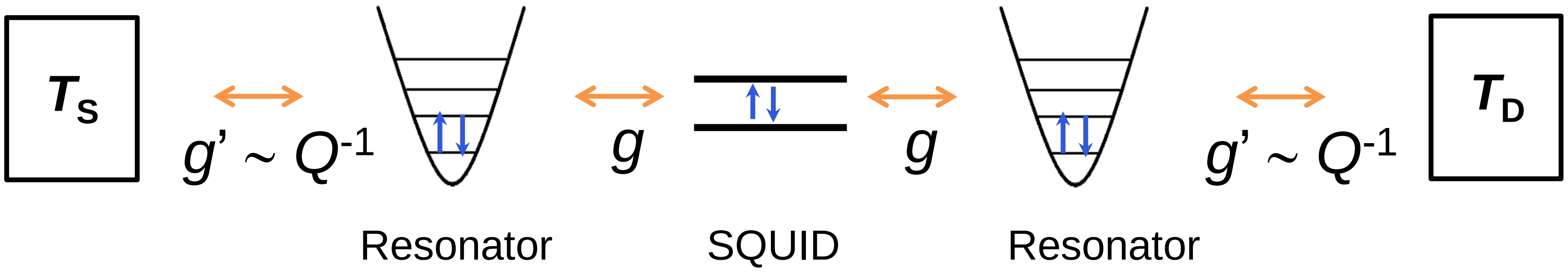
B. Karimi, J. Pekola, M. Campisi, and R. Fazio, Quantum Science and Technology **2**, 044007 (2017).



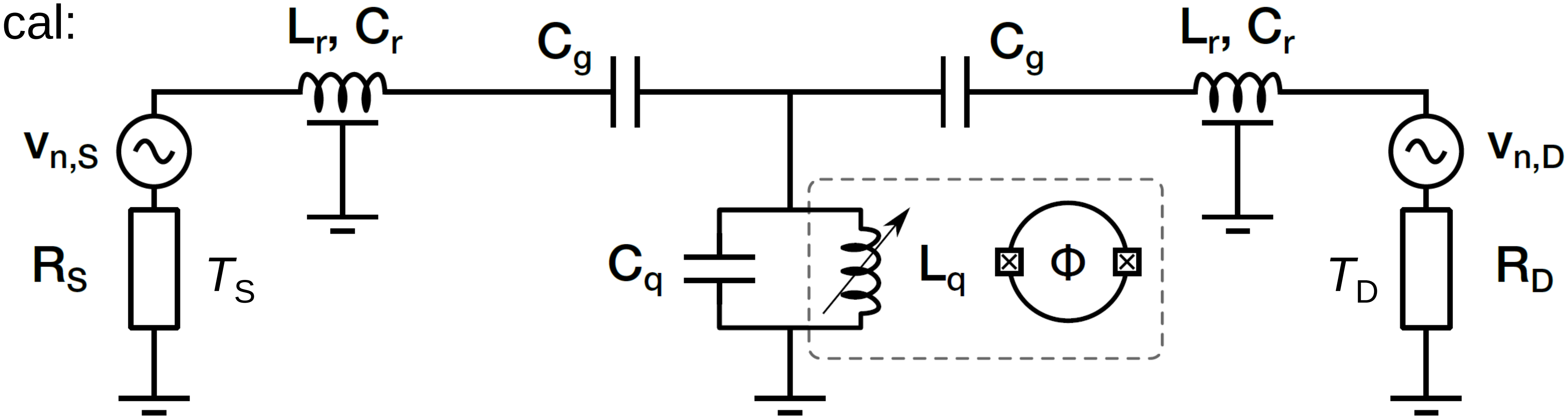
A. Ronzani, B. Karimi, J. Senior, Y.-C. Chang, J. Peltonen, C. D. Chen, and JP, Nature Physics 14, 991 (2018).

Idea of the experiment

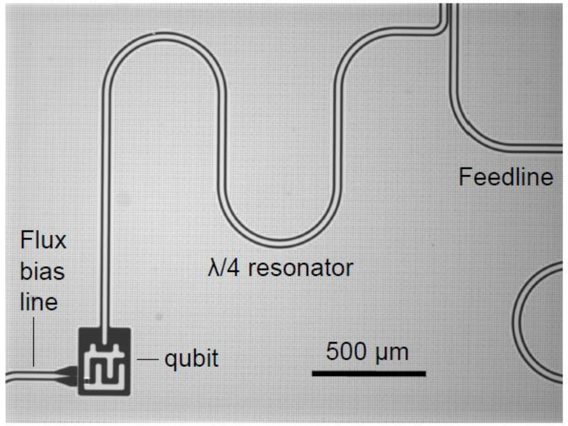
Principal:

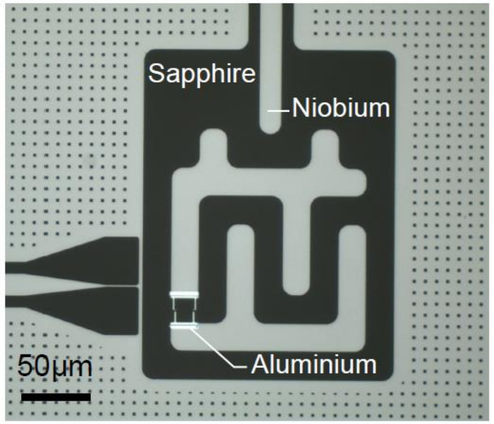


Technical:

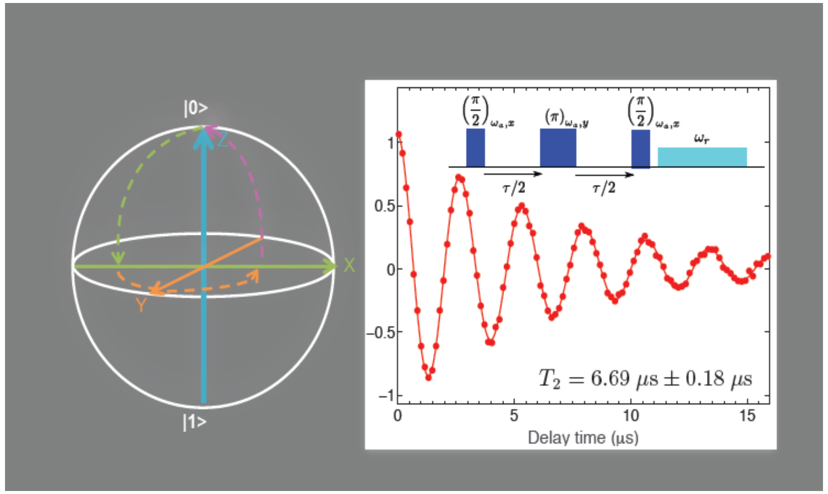


Experimental realization of the heat valve

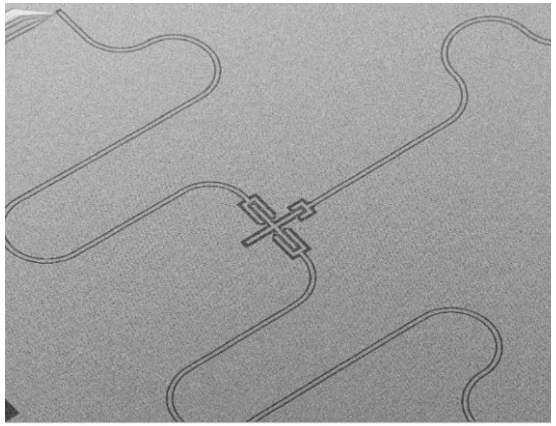




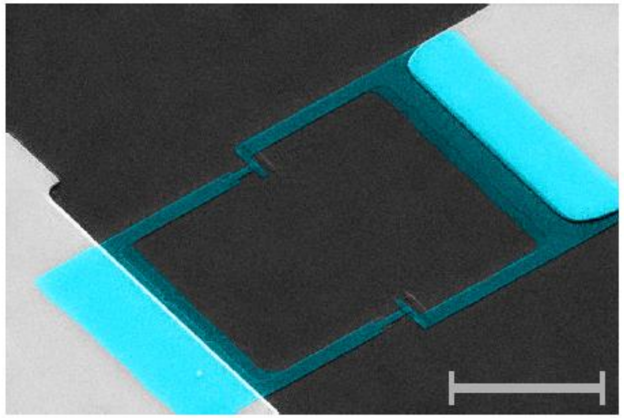
George et al. (2017)



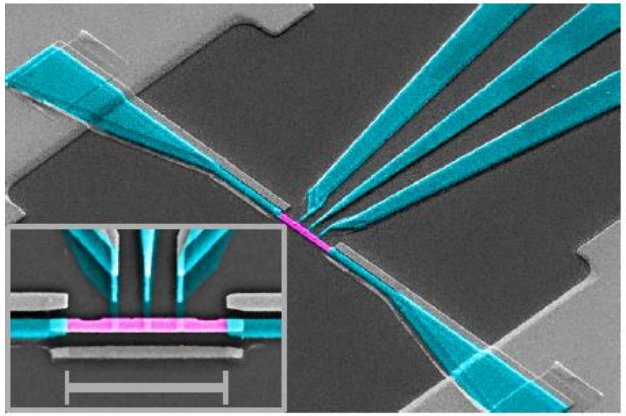
QUBIT WITHOUT ABSORBERS



1 mm



10 μm

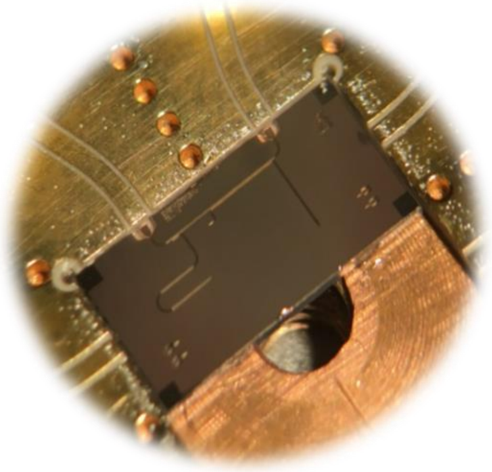


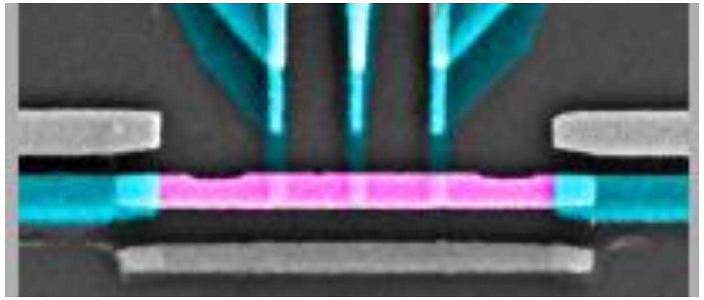
3 μm

TRANSMON QUBIT

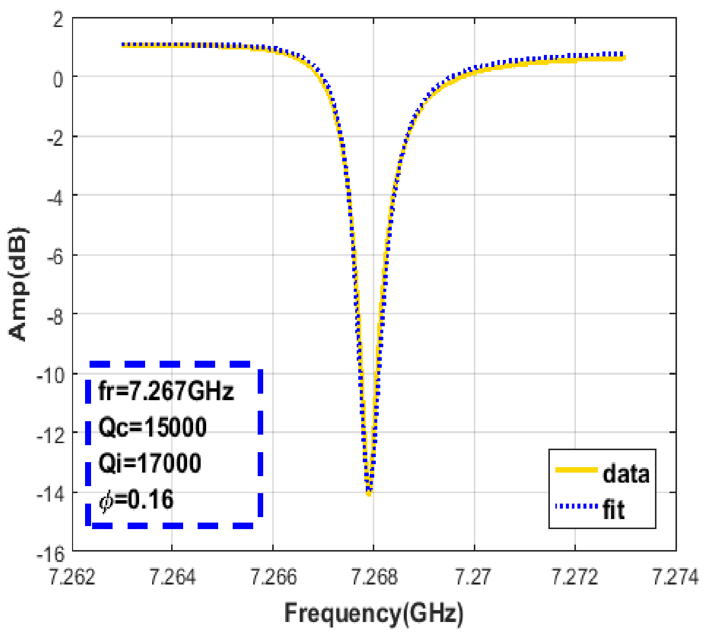
RESERVOIR AND THERMOMETERS

λ / 4 resonators terminated by heat bath *R*

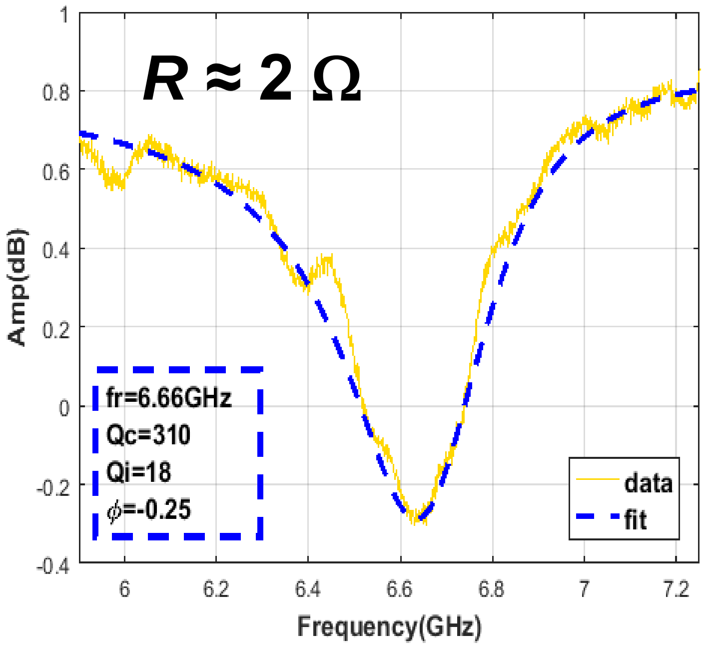




$$Q = \pi Z_0 / 4R$$



Superconducting shunt, Q = 17 000



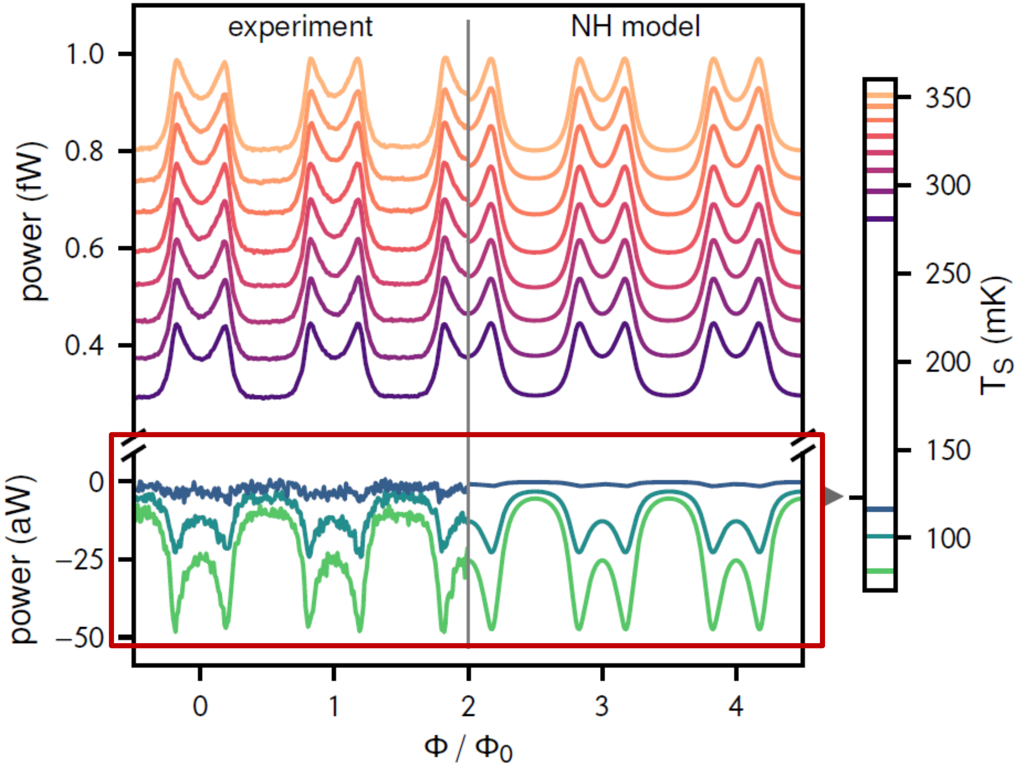
Normal (copper) shunt, Q = 18

Yu-Cheng Chang et al., arXiv:1904.0178

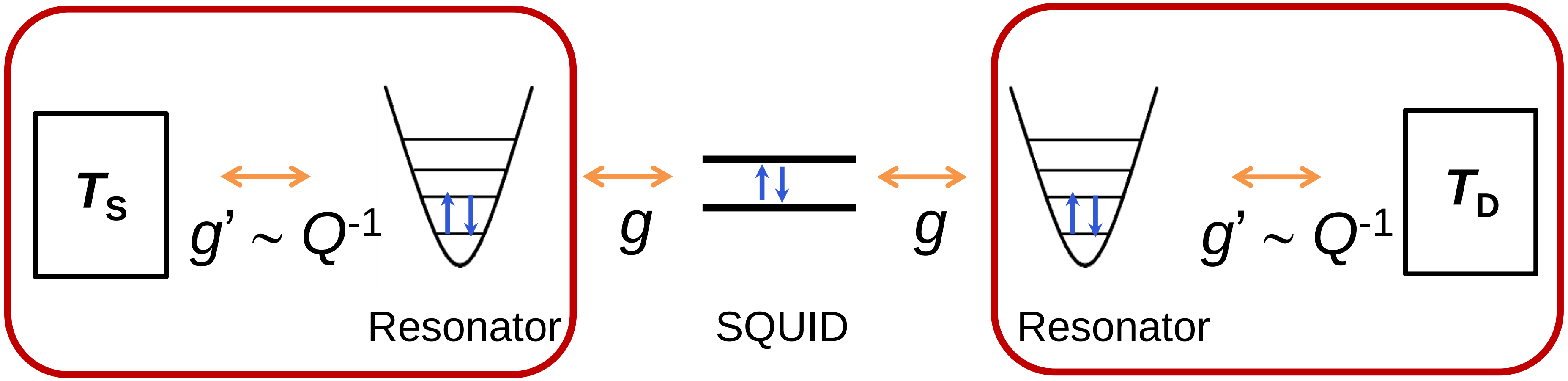
See also:
M. Partanen et al., Nat. Phys. **12**, 160 (2016); arXiv:1712.10256

Low-Q regime

$Q = 3$



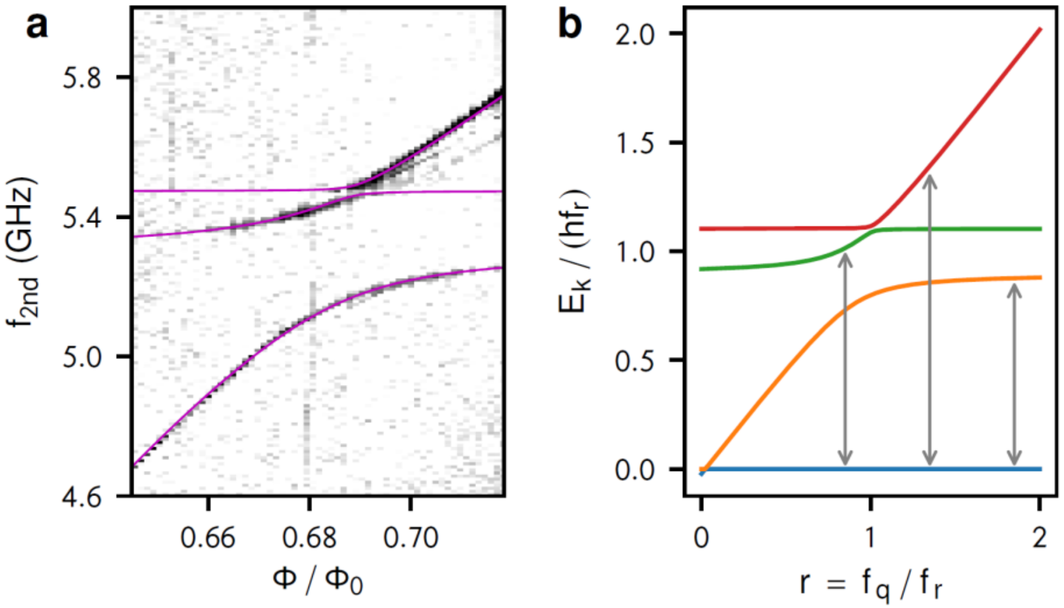
Cooling at distance of 4 mm by mw photons

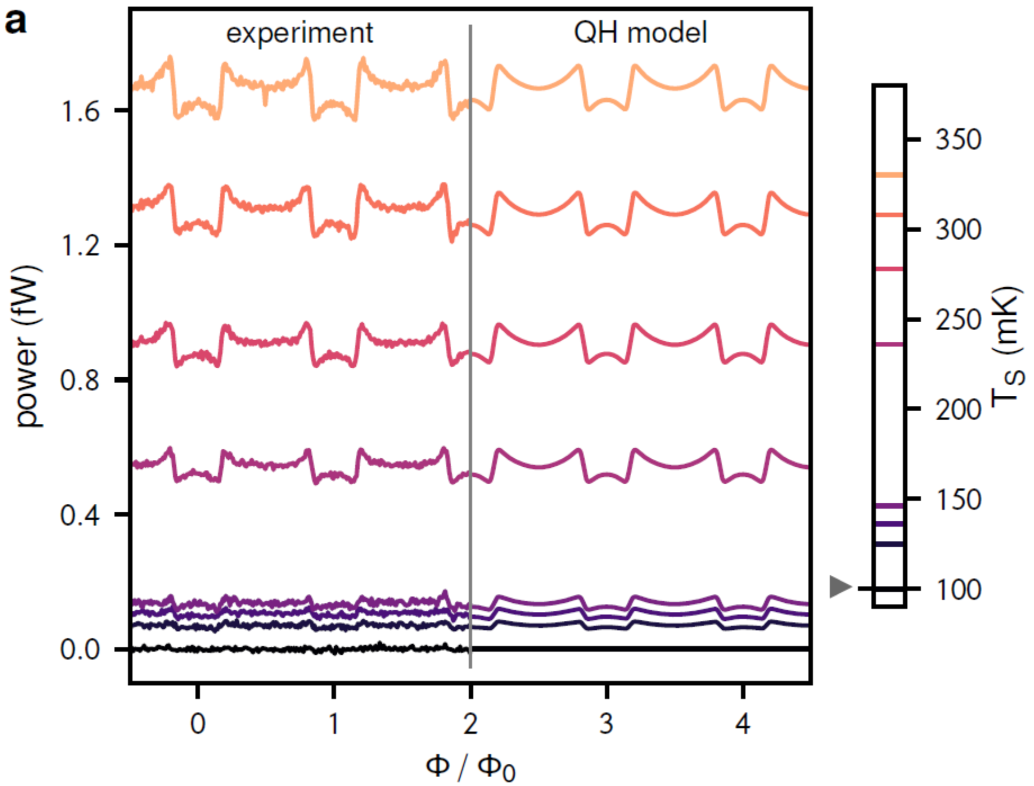


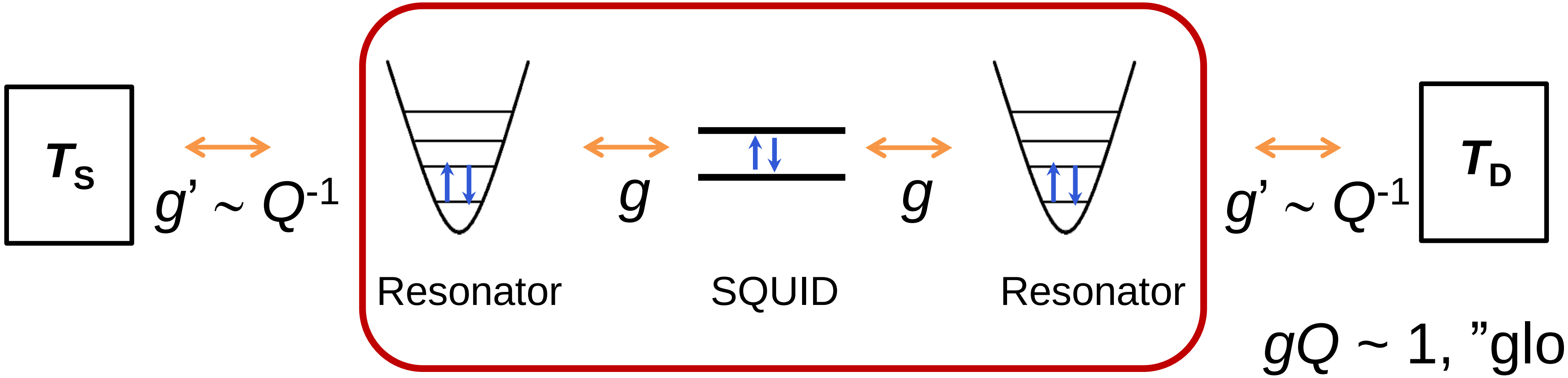
$gQ << 1$, ”local” model works

Intermediate-Q regime

$Q = 20$

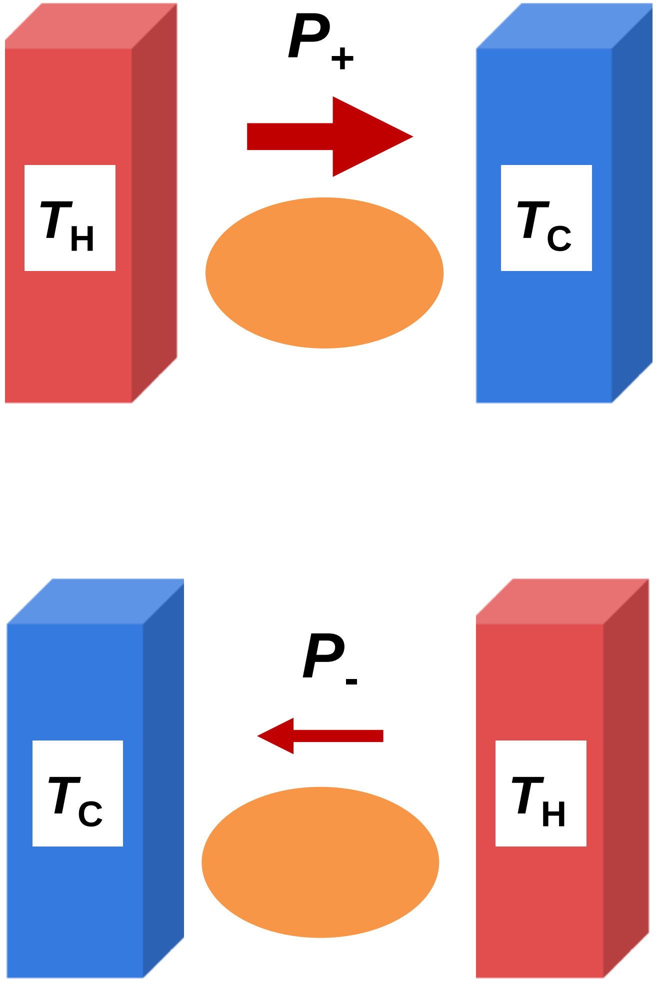






$gQ \sim 1$, "global" model works

Heat rectification

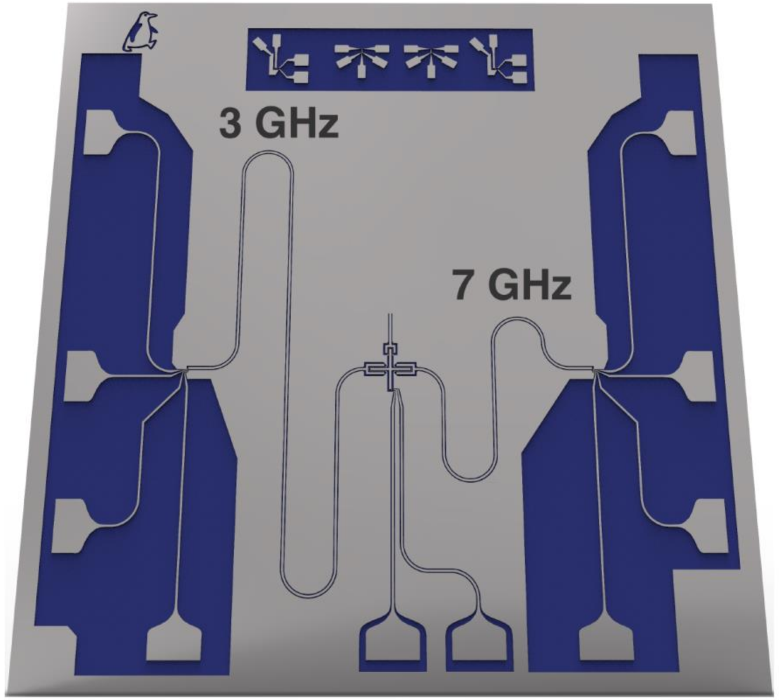


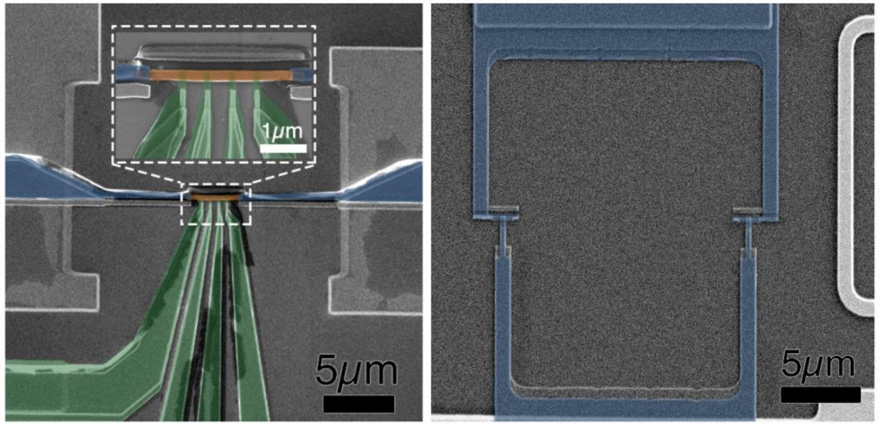
$$P_+ \neq P_-$$

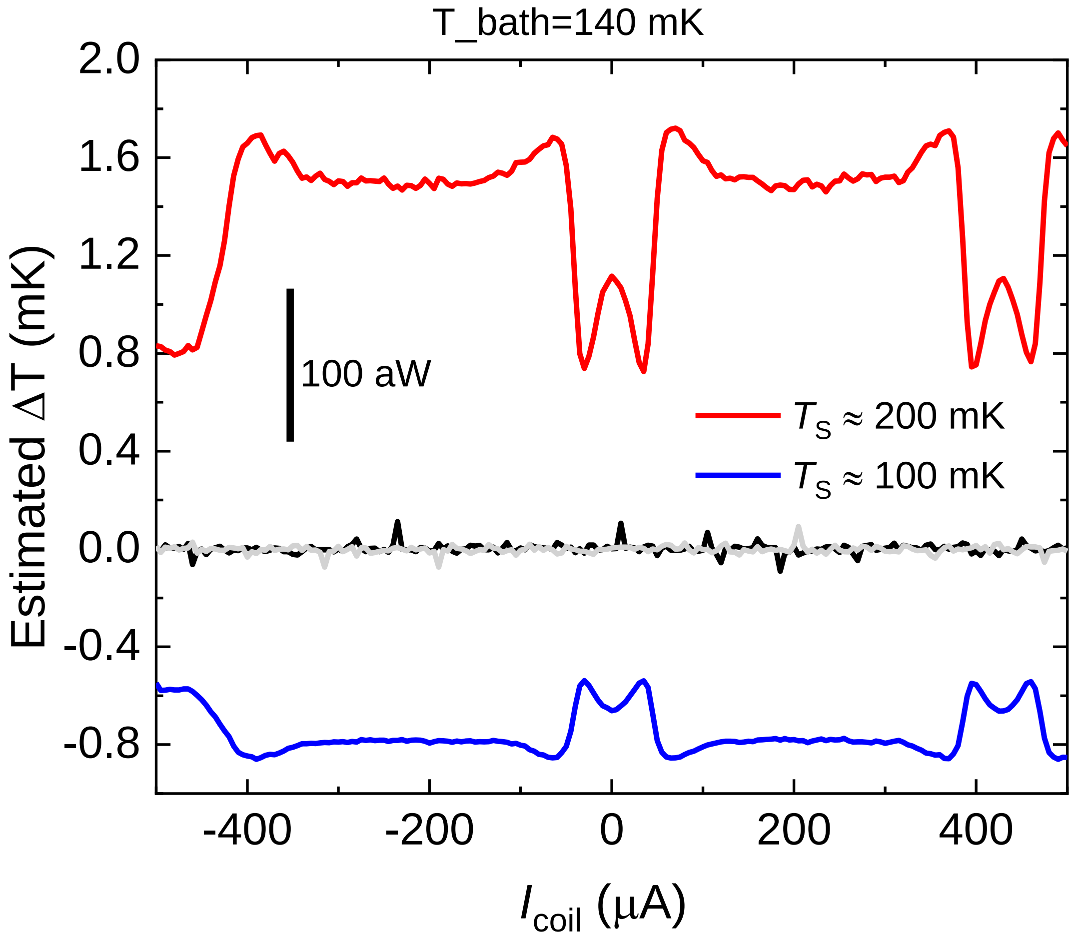
Experiments:
Carbon nanotubes: Chang *et. al.*, *Science* **314,** 5802 (2006)
Quantum dots: Scheibner *et. al.*, *NJP* **10**, 083016 (2008)
Suspended graphene: Wang *et. al.*, *Nature Comm.* ***8***, 15843 (2017)

Theories for (wireless) quantum rectifiers:
Spin-Boson model: D. Segal and A. Nitzan, PRL **94**, 034301 (2005)
Non-linear circuit: T. Ruokola, T. Ojanen, and A.-P. Jauho, Phys. Rev. B **79**, 144306 (2009)
Quantum chains: T. Motz, …, J. Ankerhold, NJP **20**, 113020 (2018)
Dynamic effects: A. Riera-Campeny, …, A. Sanpera, Phys. Rev. E **99**, 032126 (2019)
Two-atom system: C. Kargi, ..., G. Kuritzki, Phys. Rev. E **99**, 042121 (2019)

Experiment on an asymmetric device

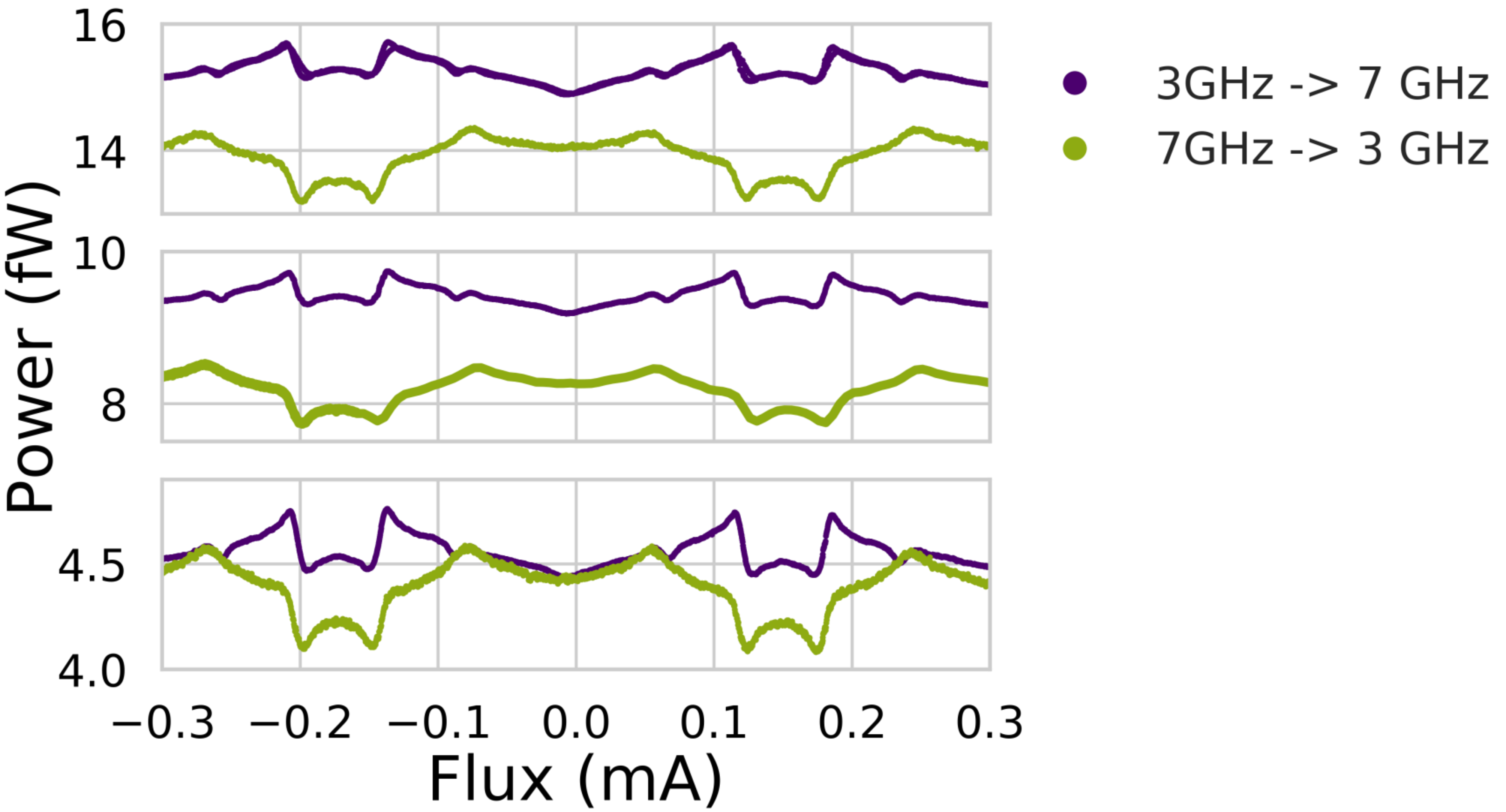






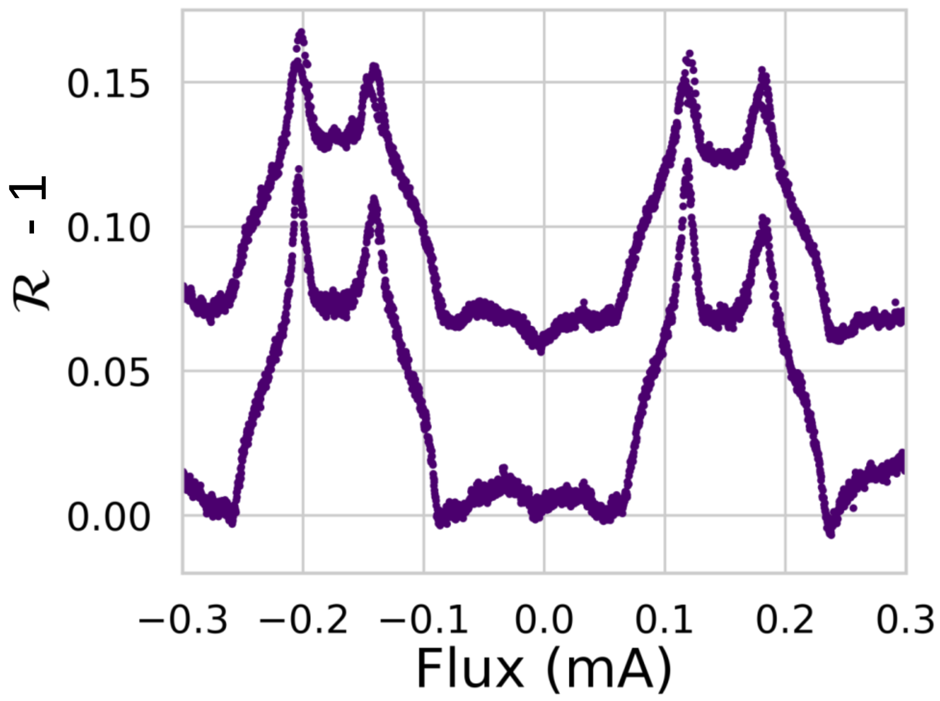
J. Senior, A. Gubaydullin, B. Karimi et al., in preparation

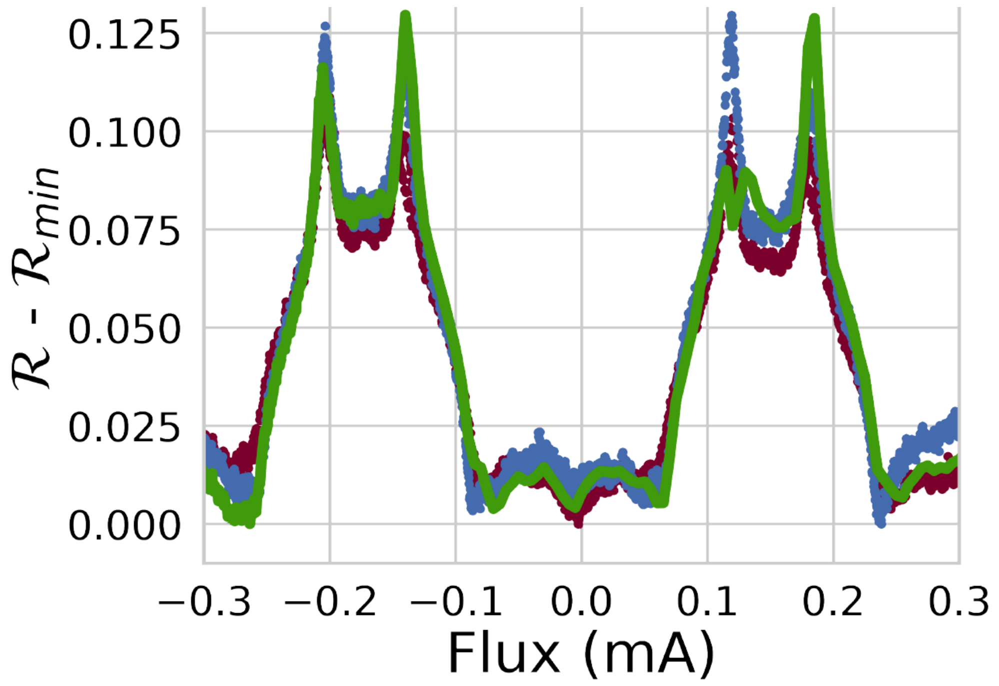
Forward and reverse powers: rectification of heat current



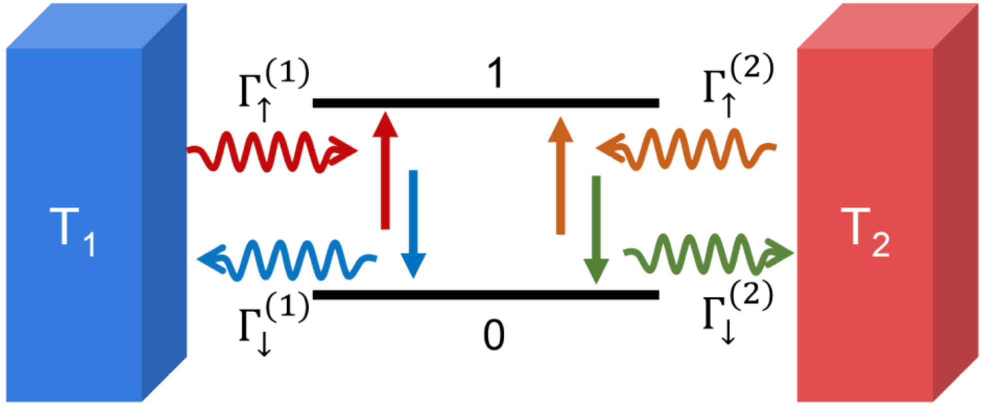
Rectification ratio from measurement

$$\mathcal{R} = |\frac{P_i^+}{P_i^-}|$$





Rectification of photonic heat current by a qubit



$$\Gamma_\uparrow^{(1)} = g_1 \frac{\omega_0}{e^{\beta_1 \hbar\omega_0} - 1}, \quad \Gamma_\uparrow^{(2)} = g_2 \frac{\omega_0}{e^{\beta_2 \hbar\omega_0} - 1}$$

$$\Gamma_\downarrow^{(1)} = g_1 \frac{\omega_0}{1 - e^{-\beta_1 \hbar\omega_0}}, \quad \Gamma_\downarrow^{(2)} = g_2 \frac{\omega_0}{1 - e^{-\beta_2 \hbar\omega_0}}$$

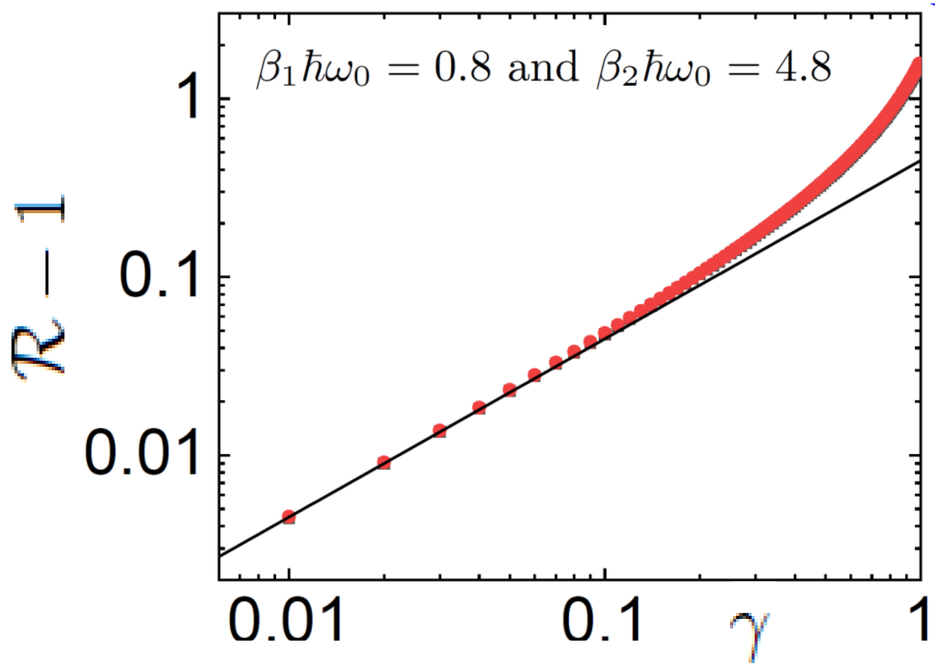
$$\rho_e = \frac{\Gamma_\uparrow}{\Gamma_\uparrow + \Gamma_\downarrow} \qquad \Gamma_{\uparrow,\downarrow} = \Gamma_{\uparrow,\downarrow}^{(1)} + \Gamma_{\uparrow,\downarrow}^{(2)}$$

$$P_i = \hbar\omega_0(\rho_e \Gamma_\downarrow^{(i)} - \rho_g \Gamma_\uparrow^{(i)})$$

$$\mathcal{R} = \left|\frac{P_i^+}{P_i^-}\right| \qquad \mathcal{R} = \frac{g_2 \coth(\frac{\beta\hbar\omega_0}{2}) + g_1}{g_1 \coth(\frac{\beta\hbar\omega_0}{2}) + g_2}$$

For small asymmetry: $\gamma = 1 - g_1/g_2$

$$\mathcal{R} - 1 = e^{-\beta\hbar\omega_0}\gamma$$

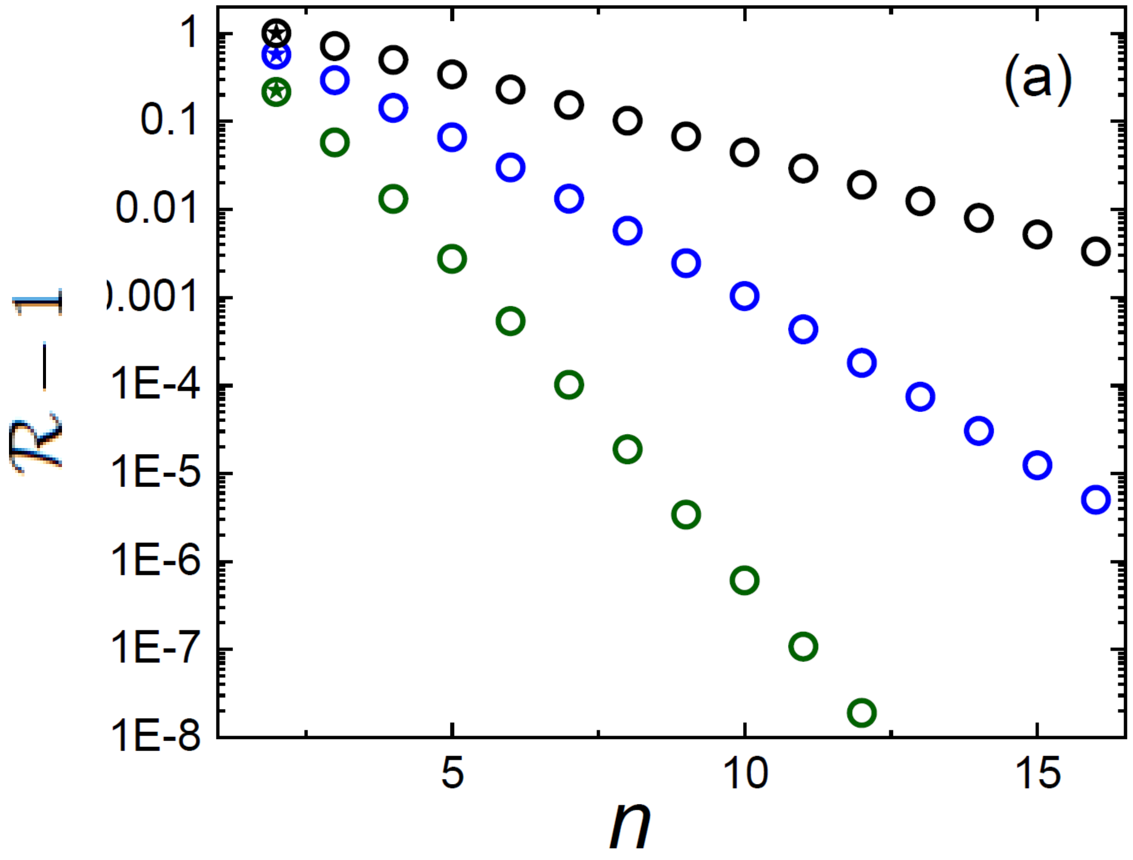


n-level system

Equidistant levels

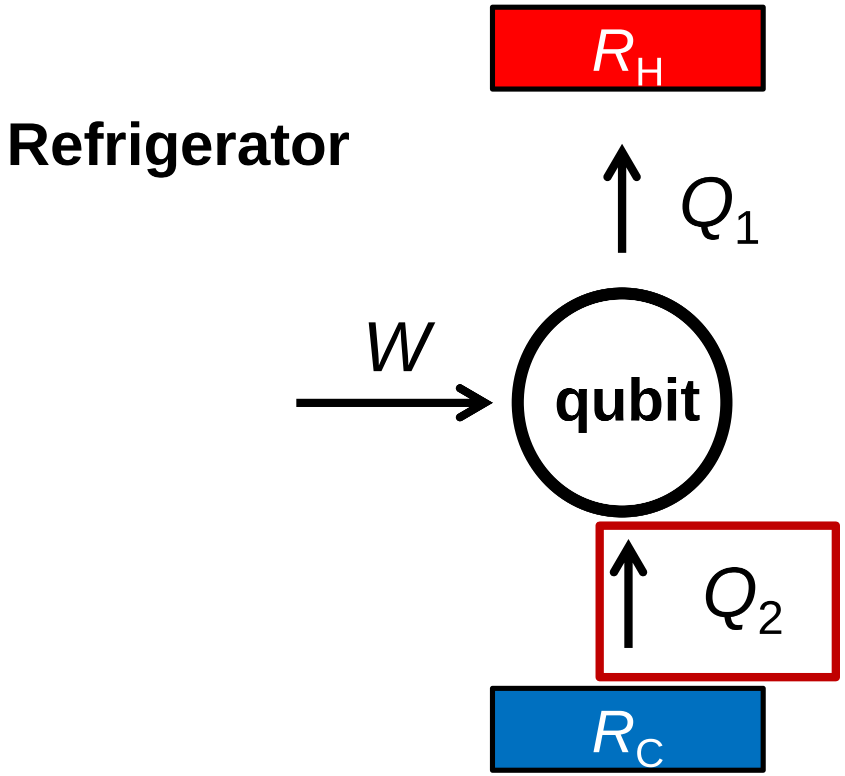
$\beta_1 \hbar\omega_0 =$ 0.4, 0.8, 1.6

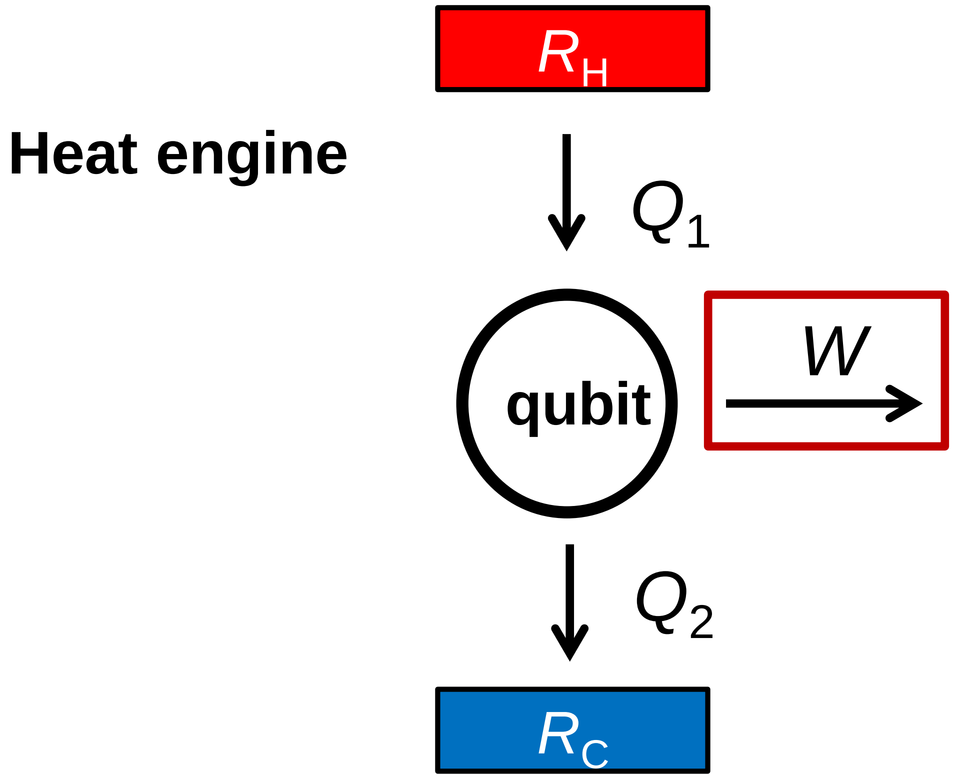
$\beta_2 \hbar\omega_0 = 4.8$



Rectification vanishes in a linear system (harmonic oscillator) even when couplings are unequal.

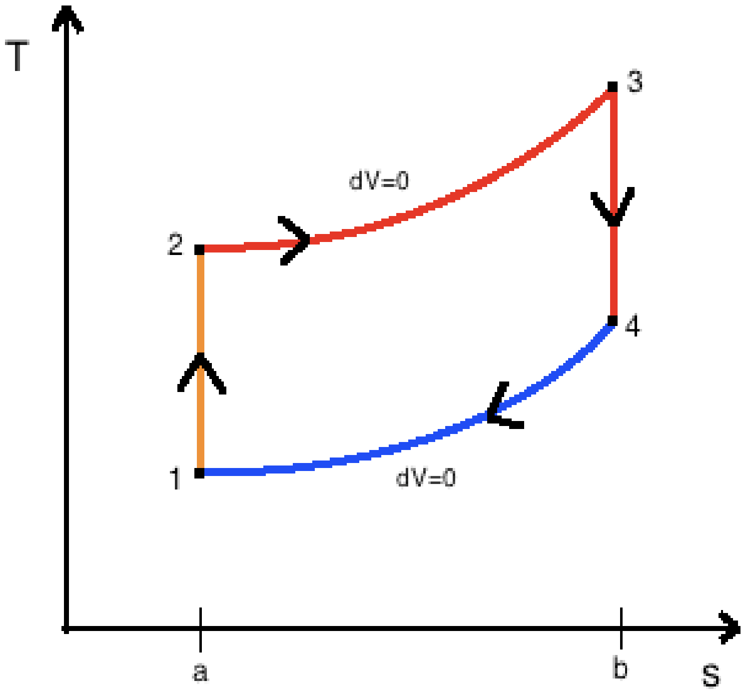
Refrigerator and heat engine

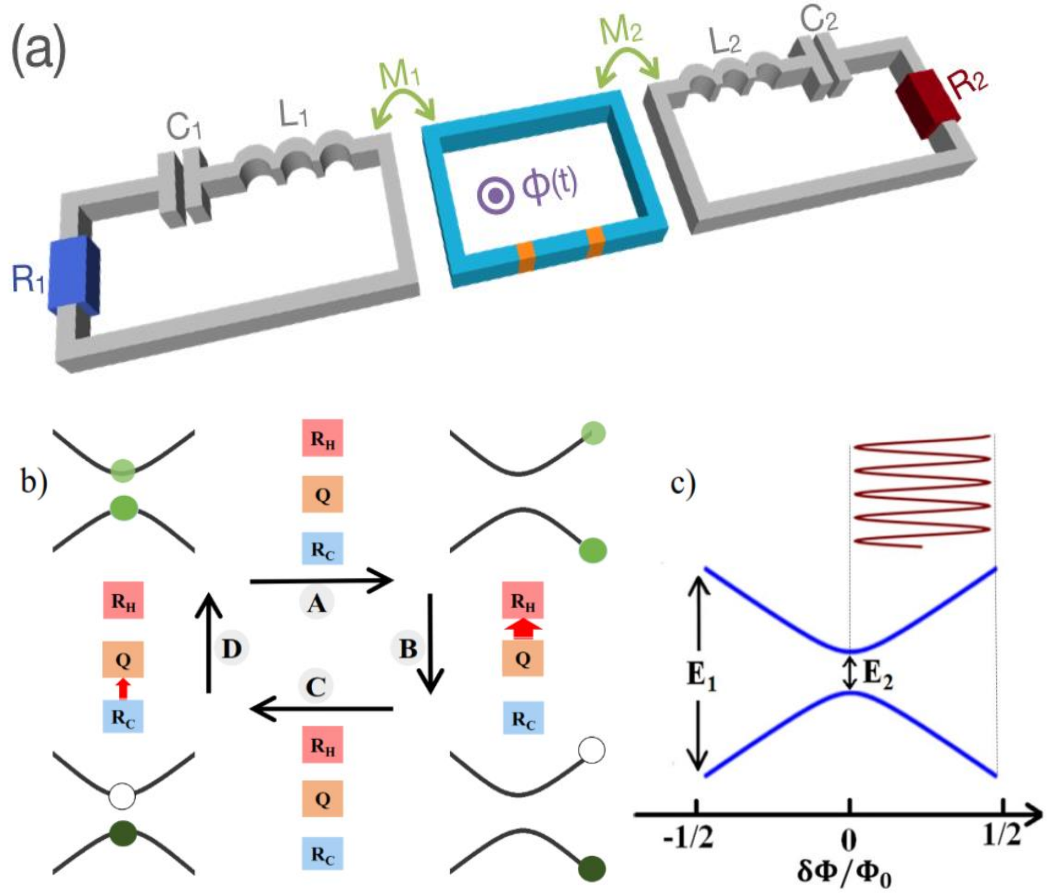




Quantum Otto refrigerator

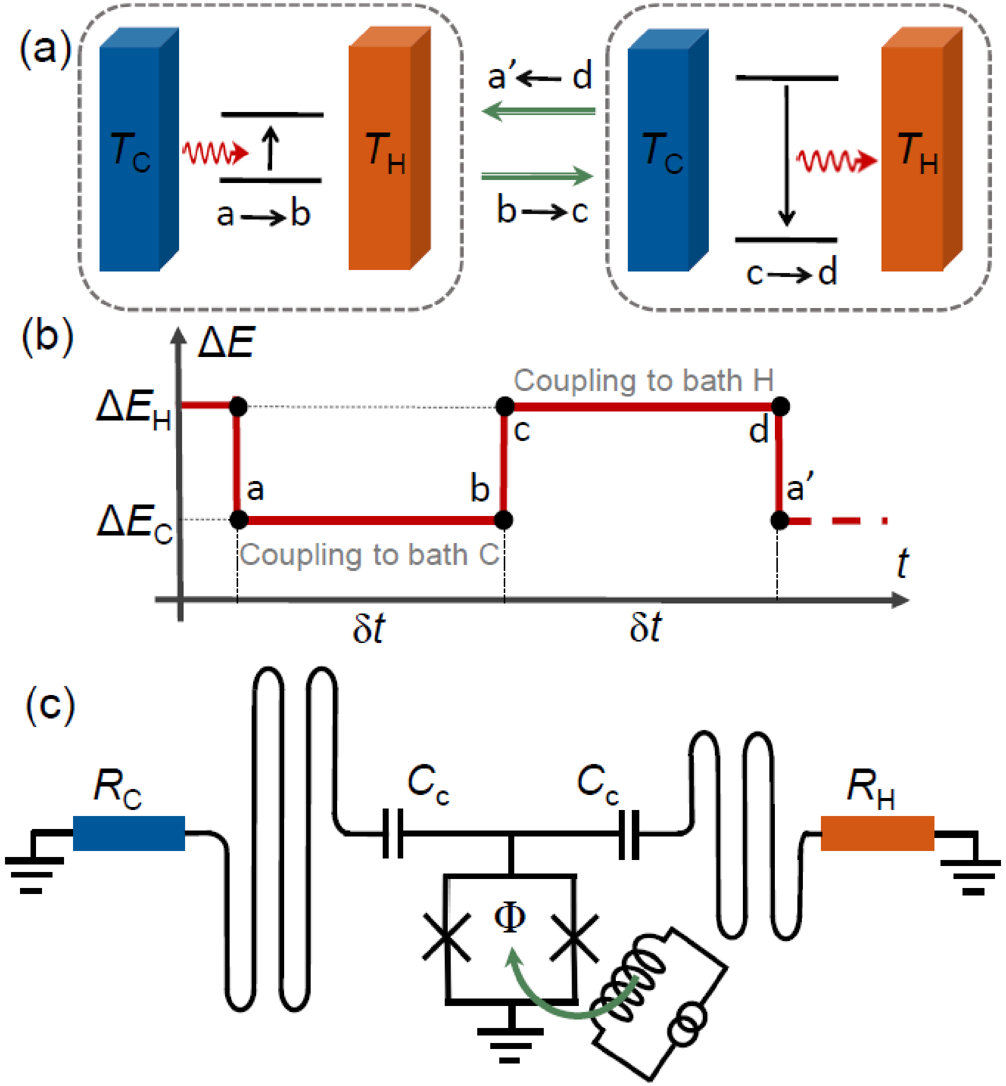
Otto cycle

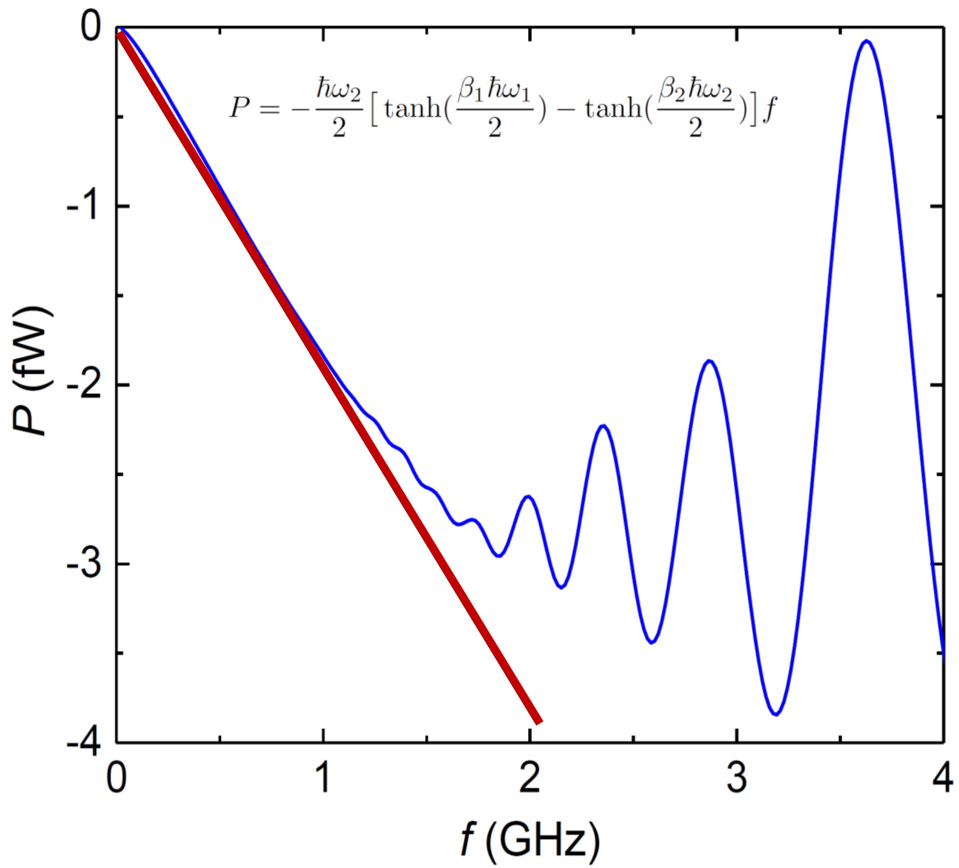




Niskanen, Nakamura, JP, PRB 76, 174523 (2007);
B. Karimi and JP, Phys. Rev. B **94**, 184503 (2016).

Quantum Otto refrigerator





Supremacy of incoherent sudden cycles (”classical supremacy”), JP, B. Karimi, G. Thomas, and D. Averin, arXiv:1812.10933

Summary

Discussed:

open quantum systems based on superconducting qubits
measurement of heat in circuits, thermometry
photonic heat transport, quantum of heat conductance
local and global picture
rectification of heat current
Quantum Otto refrigerator

Main collaborators

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ACADEMY OF FINLAND

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MARIE CURIE ACTIONS

Some open questions

System vs reservoir: where is the **interface between quantum system and reservoir?** This question is relevant for strong coupling, but as our experiment shows, it is present also in the weak coupling experiment and models.

Is there **quantum supremacy for heat engines and refrigerators?** Our Otto refrigerator example points to the opposite.

Quantum heat rectification: **how to achieve an efficient heat diode?**

Heat transport in strong coupling limit is a popular topic to study. Is it a well-posed problem? Experimental set-up to study it?

Heat transport on a quantum **trajectory** level: **stochastic nature** in single realizations

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